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Structural behavior of reinforced concrete beams strengthened with bamboo splints

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Abstract:

The aim of this paper is to evaluate through bending tests the structural behavior of reinforced concrete beams additionally reinforced with bamboo splints coated with rubber latex. The bamboo splints are prepared from the stems of the *Bambusa vulgaris* species and are reinforced in the nodal regions. To examine the strength of adhesion between the bamboo splint and concrete, pull out tests are performed for the specimens. The results of the pullout tests of the test samples show the strengthening of the nodes leading to an increase in the normal tension and rupture of the splint instead of its slip. According to the results of the bending beams, the presence of bamboo splints increases their load capacity when compared with the reference beams. This fact indicates a reduction in the amount of steel required as the structural element. Strengthening the nodes of the bamboo splints provides better performance in terms of deflection and also leads to a slight increase in the beams load capacity. It is worth mentioning that the beams additionally reinforced with bamboo splints reinforced in the nodal region present the same cracking pattern as that of reference beams.

Keywords: concrete beam, reinforcement with bamboo, structural analysis, alternative material.

Introduction

The concern regarding the effect of the uncontrolled exploitation of non-renewable natural resources that may get depleted soon, and the generation and correct disposal of the waste associated with the growth of several sectors in the economy, particularly construction, have increased the need for new materials to be researched.

Bamboo is an alternative that can partly minimize this abusive use of non-renewable materials. According to Pereira and Beraldo (2008), bamboo is a natural resource that is renewed in a shorter period of time and there is no other forest species that can compete with it in terms of growth speed and use per area. According to Pereira and Beraldo (2008), bamboo is a perennial and renewable tropical plant that produces annual shoots without the need for replanting. Additionally, it has excellent physical, chemical, and mechanical characteristics, besides being efficient at carbon sequestration. However, according to the authors, bamboo is still little used in Brazil either because of the lack of knowledge of the species, characteristics, and applications, or the lack of standardization and specific research.

In the construction industry, bamboo has been explored as a concrete reinforcement element, as an alternative to the steel reinforcement traditionally used in this sector. It is worth mentioning that Ghavami (2005) has reported that, since 1979, bamboo has been studied for its use in the form of pillars and slabs, as well as a reinforcement element for pillars, slabs, and beams.

According to Ghavami (2005), because it is an organic and hygroscopic material, bamboo, when in contact with fresh concrete, absorbs water and, consequently, its dimensions increase. When the concrete is already hardened, the reverse process occurs and the bamboo loses the absorbed water, which leads to a reduction in its volume and generates gaps that decrease the efficiency of adhesion between the two materials. Thus, in the present work, we propose coating the bamboo with a rubber latex, which acts as a waterproofing agent. The quality of the adhesion between the bamboo and concrete must be studied so that the performance of the bamboo used as a reinforcing element in reinforced concrete beams is not compromised.

Another fact to be emphasized is that, in the nodal region, bamboo has a much lower tensile strength compared with the bamboo in the internodal region. Pereira and Beraldo (2008) conducted tensile tests of laminated bamboo slats of the *Dendrocalamus giganteus* species and verified that the average tensile strength of the knotted and non-knotted slats was 111.9 and 245.4 MPa, respectively. Mesquita et al. (2006) also showed that the tensile strength of the bamboo species *Dendrocalamus giganteus* was of 97 and 277 MPa in the nodal and internodal region, respectively. On this basis, the bamboo species *Bambusa vulgaris* is expected to exhibit similar behavior.

A possible approach to minimize this disadvantage would be the use of a strengthening agent in the nodal region. For instance, segments cut from other splints and glued with a two-component polyurethane resin based on castor oil in the knotted regions can be used for reinforcement.

Therefore, the present research evaluates the structural behavior of reinforced concrete beams additionally reinforced with bamboo splints coated the bamboo with rubber latex, made from bamboo stems of the *Bambusa vulgaris* species, by conducting bending tests.

Material and methods

Dosing of concrete

The concrete dosage was based on the work by Santos, Fazzan, Melges, Akasaki, and Bertolino Junior (2010), which used the method proposed by Díaz (1998). The objective of this method was to obtain concrete with a minimum compressive strength of 25 MPa after completion of 28 days. The final dosage composition is shown in Table 1.

Cylindrical test specimens measuring 15 cm in diameter and 30 cm in height, densified using a vibrating table, were prepared to verify the characteristics of the concrete formed with the chosen dosage. The corresponding results are shown in Table 2.

Steel reinforcement

Cylindrical steel bars of 5 and 4.20 mm in diameters were used to form the reinforcements for the beams. The bars were classified as class CA 60 (f_{yk} = 60 kN cm^{-2}). The characteristics of the steel bars are presented in Table 3.

TABLE 1.
Final dosage composition of concrete.

Materials	Consumption (kg m^{-3})
Water	192
Cement	342
Sand	907.4
Gravel	1009.2
Relations	Index
Relation (1:m)	6.2
Content of dry mortar (%)	56.8
Volume of mortar (%)	65.7
Water/Cement (W/C) ratio	0.6

TABLE 2.
Mechanical properties of concrete after completion of 7 and 28 days.

	Compressive strength on 7th day (MPa)	Compressive strength on 28th day (MPa)	Modulus of elasticity on 28th day (MPa)	Splitting tensile strength on 28th day (MPa)	Water absorption on 28th day (%)
Concrete Reference Beams	16.6 ± 0.5	25.4 ± 0.5	31.5 ± 0.6	2.7 ± 0.2	5.2 ± 1.1
Concrete Reinforced Bamboo Beams	16.9 ± 0.1	27.6 ± 0.9	27.9 ± 5.3	3.1 ± 0.52	4.9 ± 1.4
Standards	NBR 5739 (Associação Brasileira de Normas Técnicas [ABNT], 2007)		NBR 8522 (ABNT, 2008)	NBR 7222 (ABNT, 2011)	NBR 9778 (ABNT, 2009)

Note: For maximum relative deviations > 6%, discrepant values and new averages were calculated as prescribed in item 3.6.4 of NBR 7215 (ABNT, 1997).

TABLE 3.
Geometric and mechanical characteristics of the steel bars [NBR 6892-1 (ABNT, 2013)].

Diameter (mm)	Area (cm^2)	Yieldstrength (MPa)*	Tensilestrength (MPa)	Modulus of elasticity (GPa)
4.20	0.138	694.9	769	189.4
5	0.196	592.8	690.3	168.5

*The yield strength was obtained graphically, considering a residual deformation of 2 per 1000.

[NBR 6892-1 (ABNT, 2013)]

Bamboo splints

Preparation of splints for the pullout test

Ten bamboo splints of 70×2×0.5 cm in nominal dimensions were prepared for the pullout tests. In each test, a 30 cm long splint was immersed in the concrete used to fill the cylindrical specimens measuring 15 cm in diameter and 30 cm in length.

All the nodes of five of the splints were reinforced in order to improve their resistance in the nodal regions, considering that part of the bamboo has a much lower resistance in comparison with the intermodal region, based on Mesquita et al. (2006) and Braga Filho, Lima Júnior, Barbosa, and Willrich (2010). The nodes of the remaining five splints were not reinforced for comparative purposes. A castor oil-based bicomponent polyurethane resin (the components of the castor oil resin were blended in a 1:1 mass ratio) was the glue applied to cast the reinforcements with a sergeant, a base beam, and supports. The latter was positioned between the sergeant and the splint so they did not get crushed (Figure 1).

Subsequently, the slabs were water proofed via latex immersion and a total of four layers of latex were applied, corresponding to an increase in 0.15 g of latex per cm^2 of the surface area of the splint. The latex was characterized and it was found to contain a proportion of 41.7% rubber to latex, with a pH of 11. The waterproofing of the splints and the characterization of latex were performed based on Ghavami (2005).

After the waterproofing, grease was coated using newspaper and crepe tape at both ends of the splint with a length of 5 cm from the ends to the center of the splint to be immerse in the concrete, leaving only 20 cm in the central part of the splint for the splint-concrete adhesion to occur (Figure 2). Thus, the adhering length was reduced from 30 to 20 cm with the aim of obtaining a lower pullout force and reducing the possibility of rupture in the external node of the concrete specimen.

FIGURE 1.
Details of the reinforcement of the splints.

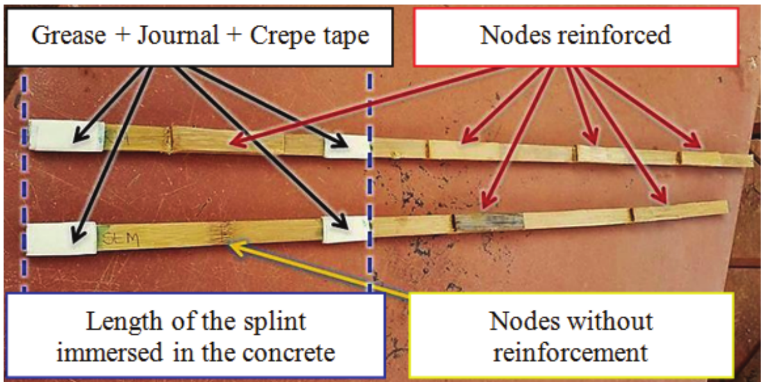

FIGURE 2.
Details of the treatments made along the length of the splints.

Reinforcement of the splints used in the concrete beams

In order to carry out the bending tests of the concrete beams, six bamboo splints with nominal dimensions of 160×2×0.5 cm and with reinforcements with a length of 10 cm attached in the nodal regions were constructed (Figure 3). The glue and the procedure used to bond the reinforcements were identical to those employed for the specimens subjected to the pullout tests.

Elaboration of beams

In total, four beams of the two following types were constructed:

- Two steel reinforced-concrete beams that were used as reference and are hereafter referred to as reference beams;

- Two steel reinforced-concrete beams additionally reinforced with bamboo splints, whose nodes were, in turn, reinforced. These beams are hereafter referred to as reinforced bamboo beams.

The percentage of the bamboo frame used in reference to the cross section of each beam was 1.6%, which was within the limit of 1.25 to 8.3% as stipulated by Raj (1991). Four forms of plywood and plasticized wood, with dimensions of 160×12.4×15 cm were used to concrete the beams.

In order to achieve longitudinal steel reinforcement on the lower face of the beams, two steel bars, each with a diameter of 5 mm were used. On the upper face of the beam, two steel bars with a diameter of 4.2 mm were used as carriers. For shear reinforcement, stirrups with a diameter of 4.2 mm, spaced every 8 cm, were used with two vertical branches. To ensure a 1 cm cover of the outermost reinforcement (in this case, the stirrup), spacers of the type EPR 24-4 were used.

For the additional reinforcement of the steel reinforced beams with bamboo splints, three splints were placed, one along the underside (centralized between the lower bars) and two along the lateral sides. The splints placed along the lateral sides were fixed at a distance of 1.5 cm relative to the bottom bar so that there were no problems during concreting (Figure 4).

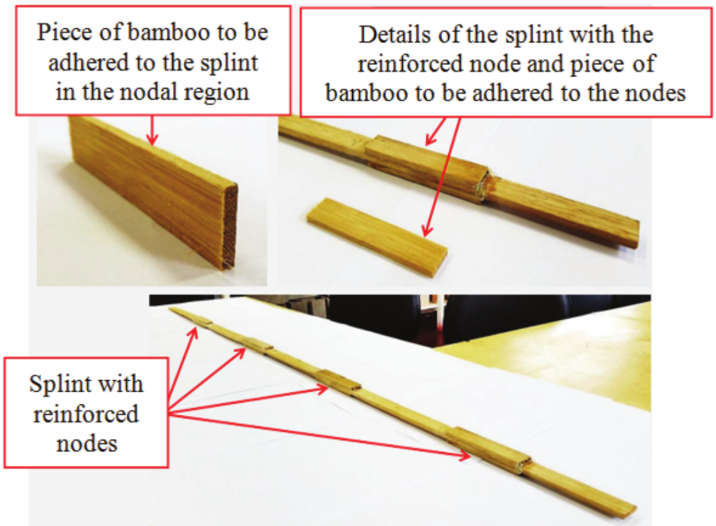

FIGURE 3.
Splints with reinforced nodes.

FIGURE 4.
Reinforcements with (left) and without (right) additional reinforcement of bamboo splints.

Of the four beams produced, the main reinforcements of two of them were instrumented with extensometers. The two beams were a reference beam and a reinforced bamboo beam, which were used as additional reinforcement for the armature.

Subsequently, all the beams were concreted and densified using a vibrating table. After a three-day period, the beams were deformed and placed in a humid chamber where they remained for a period of 28 days.

It should be mentioned that before the concreting of the reinforced beams with the bamboo splints, an epoxy resin was applied at the ends of the splints to improve their anchoring ability in the supporting region.

Pullout tests on specimens

Ten test specimens were prepared using metallic molds with dimensions of 15 cm in diameter and 30 cm in length. Five of these were reinforced at all nodes and five with reinforced splints in the nodes that were not in contact with the concrete. The splints were positioned in the center of the mold so that a part of their length was immersed inside the concrete used to fill it. The unmolding was achieved using an immersion vibrator. The unmolding was performed the day after the immersion and the specimens were placed in a humid chamber for 28 days.

After this period of time and before the arrangement test, the specimens were capped with gypsum, above which a metal plate was placed while the plaster was still in a plastic state. A kneecap was used to adjust the event of the specimens and, on top of it, to a rectangular metal plate, a uniform distributor or load from the test machine to the test sample.

The pullout tests, based on BS 1881: Part 207 (British Standards Institution [BSI], 1983), were performed using a universal machine with a capacity of 100 tf. The lower end of the splint, embodied within the specimen, was positioned below the central part of the test machine, while the other end, made up of the apparent bamboo, was secured by the grip on the upper part of the machine (Figure 5).

A comparator watch, used to measure the displacements, was positioned between the central and upper parts of the machine to measure the elongation of the portion of the splint that was not immersed in concrete.

The test was conducted with load increments of 50 kgf until the bamboo ruptured or slipped. After the pullout test, the specimens were sectioned longitudinally via the diametrical compression test, thereby allowing an analysis of the state of the slabs embedded in the concrete and those which had slipped.

After the rupture of the splint or its slipping, adhesion and normal tensions were performed.

Bending tests of the beams

The static scheme used in the bending test is presented in Figure 6. It is proposed that the central region mimics pure flexion.

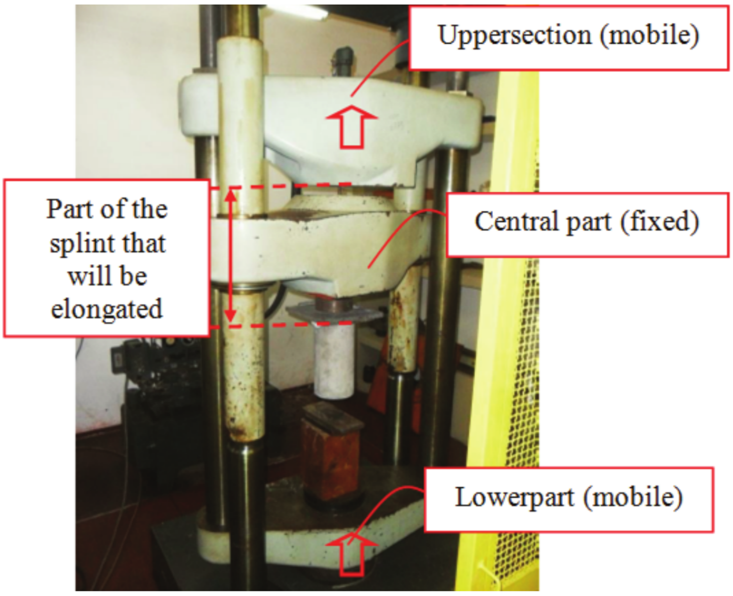

FIGURE 5.
Test sample positioned in the press for a pullout test.

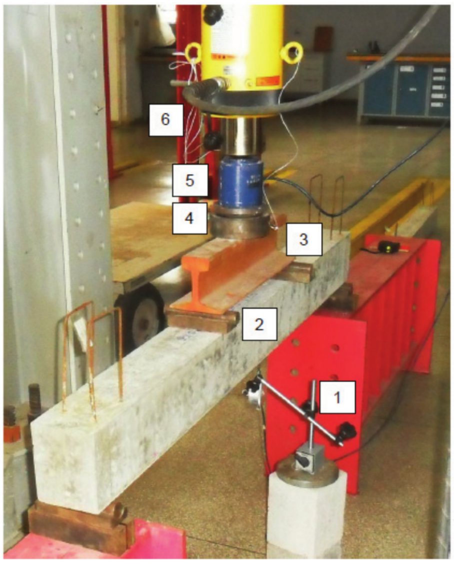

FIGURE 6.
Devices used in the bending test: 1) comparator watch, 2) roller, 3) metallic profile used to transfer the load to the beam at two points defining the central region, 4) patella, 5) load cell and 6) hydraulic jack.

The force is applied by a hydraulic actuator (or jack) coupled to a 30 tf load cell. A metal profile is used to distribute the force in the central span of the beam. A metal ball is placed between the load cell and the metal profile, allowing the hydraulic cylinder to be accommodated due to the possible imperfections in the profile's surface. The vertical displacement in the middle region of the beam is measured using a dial indicator. The strain gauges, load cell and comparator watch were connected to DAQbook 120 Data Acquisition System (Iotech) by interfacing with the DASYLab 5.0 program.

The beams were tested after 28 days, during which a loading speed of 1 kgf/s was applied. For the accommodation of the beams in the system and the elimination of any slack between the devices, a loading cycle was performed, also known as a primer. After the priming, the beams were loaded until no load gains could be observed by the hydraulic actuator or until the beam ruptured.

Results and discussion

Pullout tests on specimens

The normal tension and adhesion stress graphs corresponding to the pullout tests are shown in Figure 7 and 8, respectively. The mean values of the normal stresses at the time of rupture (or slip) of the specimens with and without internal reinforcement of the bamboo splint nodes were 97 and 76.5 MPa, respectively, i.e., reinforcement of the internal nodes resulted in an increase of 28% of the normal stress. Mesquita et al. (2006), in tests with concrete specimens and bamboo splints studded with steel and bamboo pins, found that the positions of the steel and bamboo pins increased the adhesion tension by 80 and 50%, respectively. Comparing the results of the slabs with those obtained by means of a smooth steel bar, the authors verified that the steel and bamboo pins presented tensions of adhesion superior to those of smooth steel in 25 and 5%, respectively.

The average value of the adhesion tension at the moment of slip for the specimens without internal reinforcement of the bamboo splint nodes was 0.9 MPa. For the specimens reinforced at all the nodes, the tensile rupture was observed in the splints.

Considering the specimens reinforced at all the nodes, the following rupture forms were observed: for CP 01, the rupture occurred in the reinforced internal node; for CPs 02, 03, and 04, the rupture occurred in the reinforced external node after the detachment of the reinforcements; and for CP 05, the rupture of the splint was observed outside the nodal region, more specifically in the region of its attachment to the press clamp, although one of the reinforcements already showed a detachment.

Beam bending

The main parameters obtained by the beam bending tests are presented in Figure 9 a t 12.

However, before discussing the results, it is important to mention that when a 6 mm deflection, corresponding to a deflection/span ratio of 1/250, is achieved in the middle of the beam, it is considered that the beam has reached a Serviceability Limit State in excessive visual displacement. Additionally, to avoid causing possible damage to the measuring equipment during the test, the dial indicator was removed after an 8 mm deflection was reached.

The results obtained show that the additional reinforcement with bamboo splints waterproofed with latex and reinforced at the nodes causes a 58% increase in the resistance of the beam, suggesting that it can support a greater load than in the absence of the additional reinforcement. Ghavami (2005) carried out tests on beams with and without steel reinforcement using two percentages of bamboo frame in relation to the cross section of the beam (3.33 and 5%) and it was verified that the ideal amount to be used as reinforcement of beams is a 3% bamboo rate in relation to the concrete cross section. It was also verified that bamboo-reinforced beams supported a load 400% greater than the beams without any reinforcement. Agarwal, Nanda, and Maity (2014) performed bending tests on reinforced beams, reinforced with steel, reinforced with treated bamboo and reinforced with untreated bamboo. The results of the bending tests showed that the beams reinforced with treated bamboo obtained a significant increase in the rupture force when compared to the steel beams. Quantitatively, with a treated bamboo reinforcement of only 1.5% there was an increase of 29% in the resistant capacity.

With respect to the moment corresponding to a deflection of 6 mm in the middle of the beam (Serviceability Limit State), the presence of the reinforcement results in an increase of 7.1%. This suggests that the Serviceability Limit State would be reached first for the reference beam and only then for the reinforced bamboo beam. For a deflection of 8 mm, it is observed that the additional reinforcement provided by the bamboo splints with reinforcement at the nodes causes an increase of 10.5%.

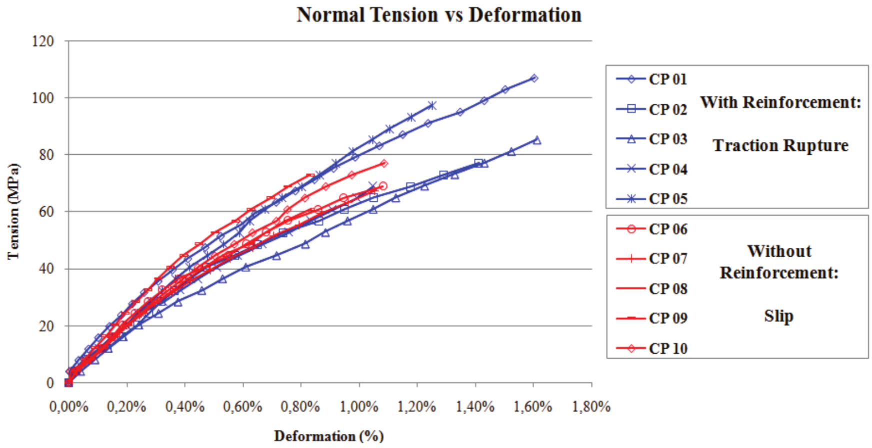

FIGURE 7
Pullout test: normal tension.

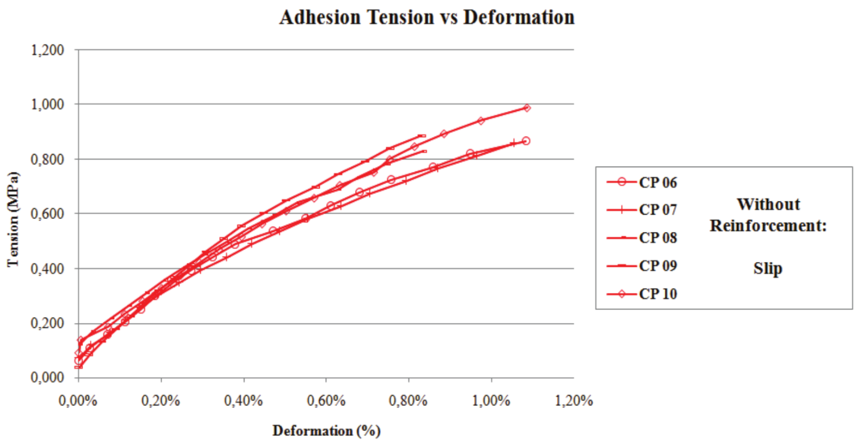

FIGURE 8.
Pullout test: adhesion tension only for sliding specimens.

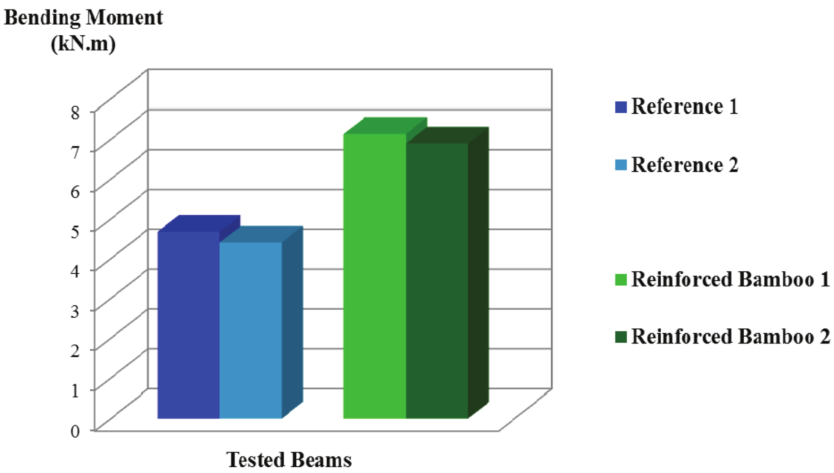

FIGURE 9.
Comparative graph of the maximum bending moment (rupture) supported for each beam tested.

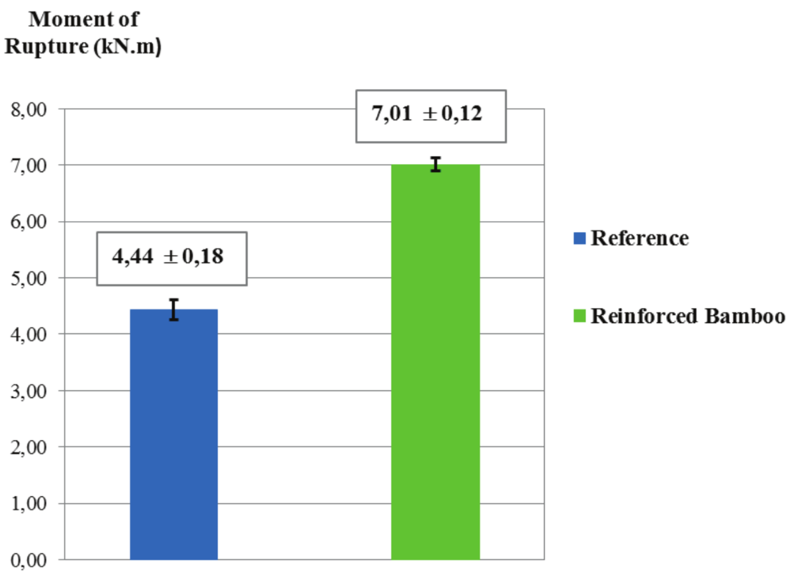

FIGURE 10.
Comparative graph of the mean values and deviations of the bending moment of rupture of the beams tested.

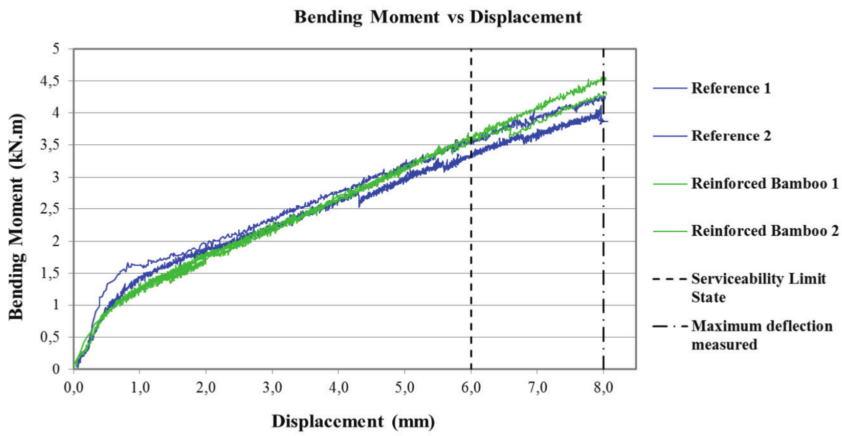

FIGURE 11.
Comparative graph of the variation of bending moment versus displacement (or deflection) of all the beams tested.

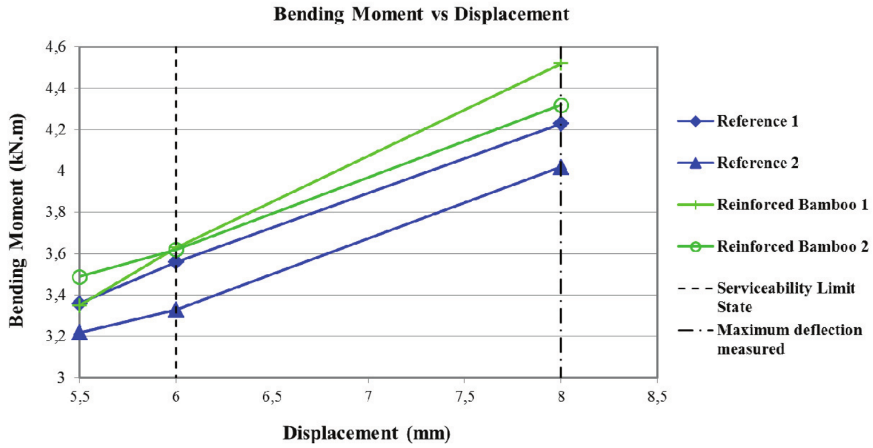

FIGURE 12.
Comparative graph of the variation of the bending moment versus displacement (or deflection) of all the beams tested between 6 and 8 mm deflections.

Regarding the beginning of the cracking, the effect of bamboo is not favorable because the cracking time for the reinforced bamboo beam is 25% lower than that of the reference. It can be observed that the deflection at which cracking occurs is practically the same. Braga Filho et al. (2010), when analyzing the structural performance of concrete beams, noticed an increase in the stiffness index when bamboo talismans studded with steel and bamboo pins were added as reinforcement in beams.

The deformations in the concrete, the lower longitudinal reinforcement, and the bamboo splints were evaluated using extensometers positioned in the middle of the beam. Figure 13 and 14 present the data obtained through the extensometers present in the reference and reinforced bamboo beams, respectively.

In the case of reference beam 1, for the traction reinforcement in the situation corresponding to the last bending moment, a typical flow level is observed with deformations above 8 per thousand.

The concrete exhibits a linear behavior and only near the rupture there is a sudden elevation of the neutral line and, consequently, there is a reduction in the compressed concrete area and in its crushing. Before the crushing began, the deformation in the concrete was 1.25 per thousand.

For the reinforced bamboo beam 1, the deformation in the concrete is 1.73 per thousand. For the steel beam, however, it is above 6.25 per thousand, which almost coincides with the deformation of the bamboo positioned on the underside of the beam, which shows that the bamboo was well adhered to the concrete.

The lateral bamboo undergoes a deformation of 4.75 per thousand, a value that is coherent as the position of its center of gravity is above the lower bamboo (and steel).

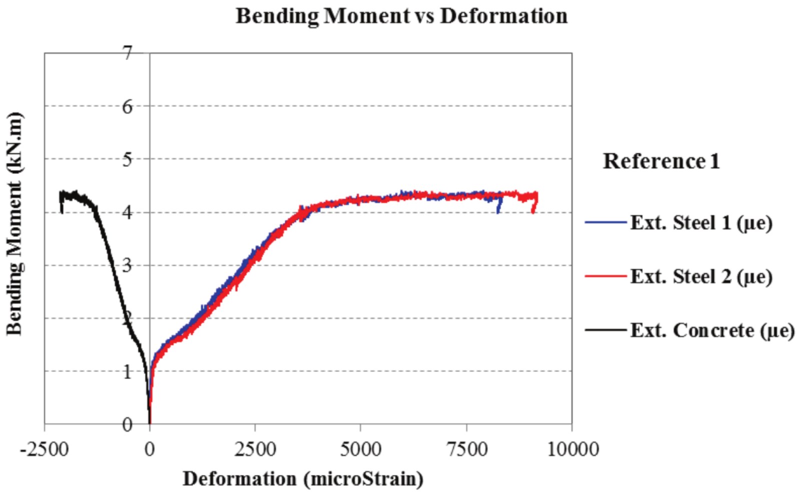

FIGURE 13.
Data from the extensometers positioned in reference beam 1.

Thus, owing to the fact that the bamboo absorbs part of the tensile stress, the deformation in the steel might be smaller. For reinforcement, a well-defined flow threshold is not observed as in reference beam 1. However, plastification starts. Furthermore, the crushing of the concrete resulting from the ascent of the neutral line is observed, with deformation in the concrete that is larger than that of reference beam 1. That is due to the resulting increase in strength of the compressed concrete to balance the resultant tensile provided by the steel reinforcement and the bamboo.

Cracking pattern of beams

Figure 15 and 16 show the behavior of the reference and reinforced bamboo beams regarding their cracking pattern.

It is possible to verify that the rupture of the beams occurs in the central region, as expected, precisely in the region submitted to the largest bending moments. Apparently, the cracking pattern is basically the same for all the beams tested, although the reinforced bamboo beams show a larger number of cracks and less spacing between them.

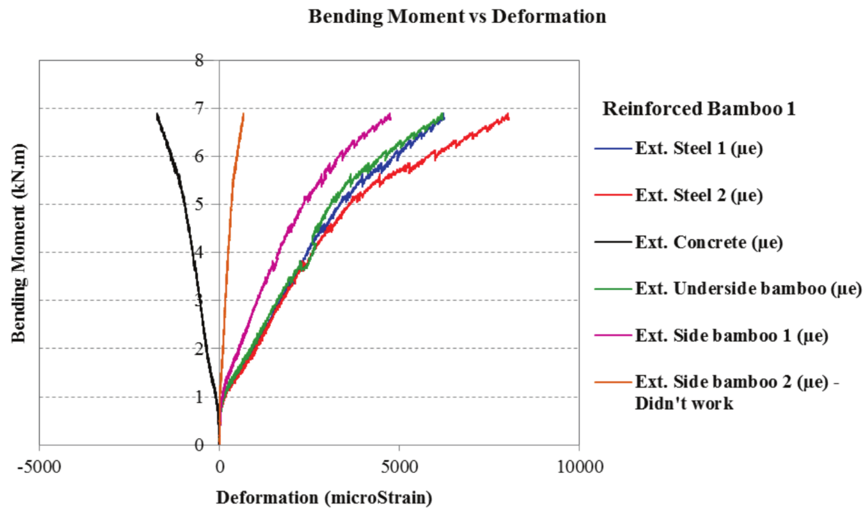

FIGURE 14.
Data from the extensometers fixed in reinforced bamboo beam 1.

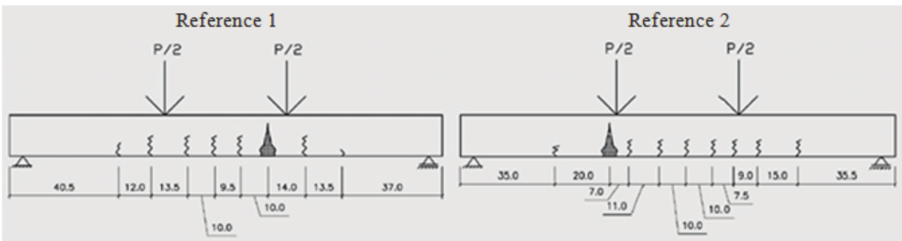

FIGURE 15.
Cracking of reference beams 1 and 2 measured in centimeters.

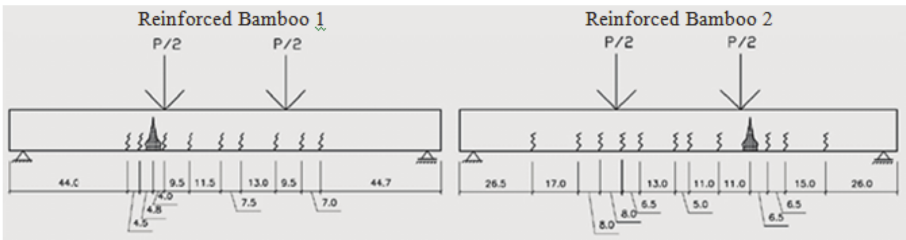

FIGURE 16.
Cracking of reinforced bamboo beams 1 and 2 measured in centimeters.

Conclusion

The pullout tests showed that the reinforcement at the nodes of the bamboo splints resulted in a 28% increase in normal tension. The bending tests showed that the reinforcement with bamboo:

- Increased strength of the beams by 58%;
- Resulted in a slight improvement in their serviceability;
- Induced cracking at smaller load;
- Caused the reinforcements at the nodes to become efficient at larger deflections.

Thus, it can be concluded that the bamboo reinforced at the nodes increased the resistance of the beams, indicating a possibility of reduction in the amount of steel required as the structural element.

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